



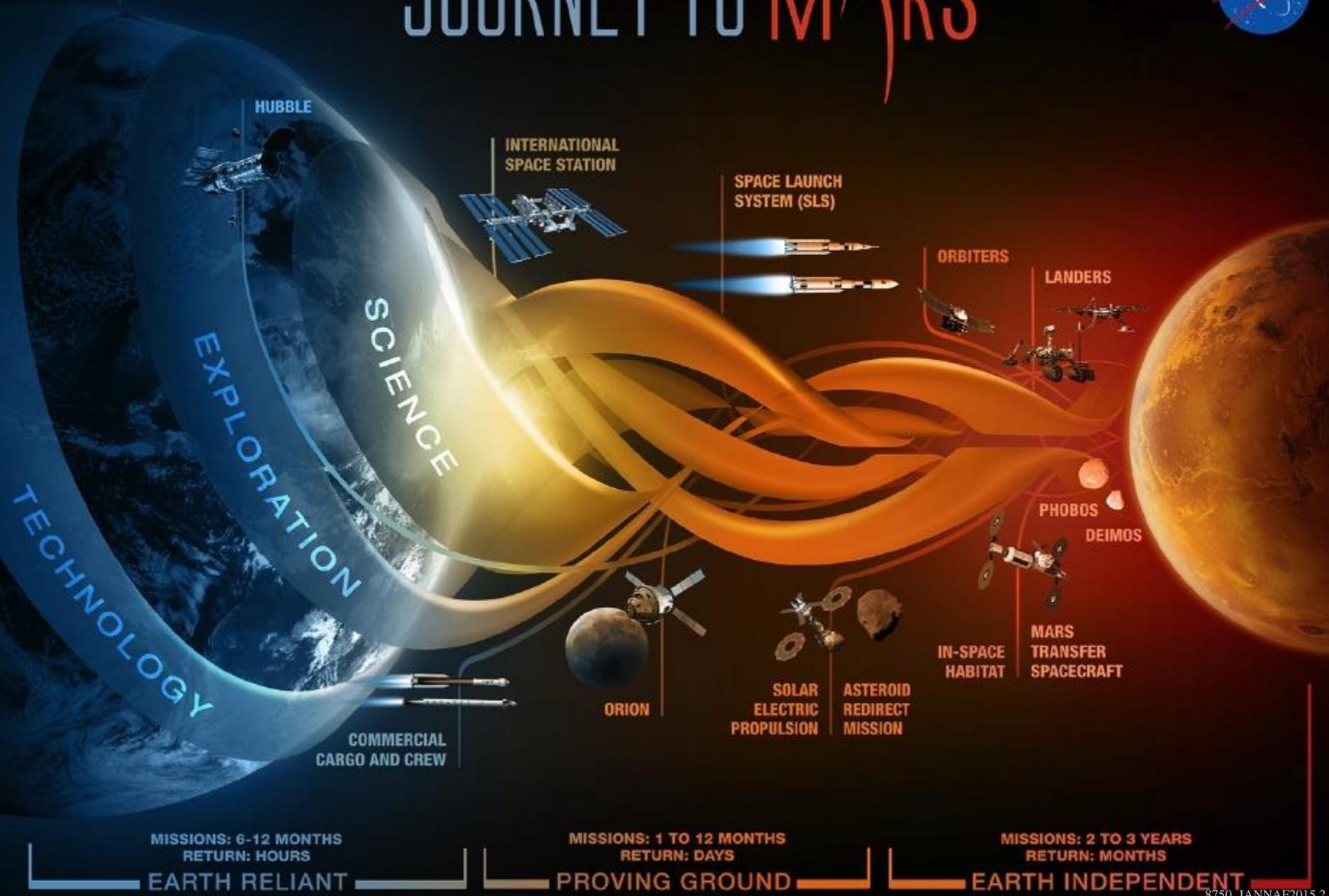
**Development and Certification of Additive Manufacturing
Materials for Human-Rated Launch Vehicles and
In Space Manufacturing
Manufacturing Problem Prevention Program
The Aerospace Corporation
October 6, 2015**

marshall



- **NASA's Journey to Mars – Where will Additive Manufacturing Contribute?**
- **In Space Manufacturing Initiative (ISM)**
 - 3D Printer International Space Station Technology Demonstration
 - ISM Elements
 - ISM Roadmap
- **Additive Manufacturing of Liquid Rocket Engine Components**
 - Advanced Manufacturing Demonstrator – Liquid Propulsion System and Low Cost Upper Stage Propulsion Project
 - RS-25 Affordability Initiative – Additive Manufacturing's Increasing Role
 - Draft Certification Approach for Additively Manufactured Rocket Engine Components
 - Additive Manufacturing Structural Integrity Initiative (AMSII) for Rocket Engines
- **Snapshot of Additive Manufacturing Activities Around the Agency**
- **Summary**

JOURNEY TO MARS



EARTH RELIANT

PROVING GROUND

EARTH INDEPENDENT

Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- In-space Recycling Technology Development
- External In-space Manufacturing and Repair
- **AM Rocket Engine Development, Test, and Certification**
- **AM Support Systems Development and Test**

International Space Station



Space Launch System



Asteroids



Commercial Cargo and Crew



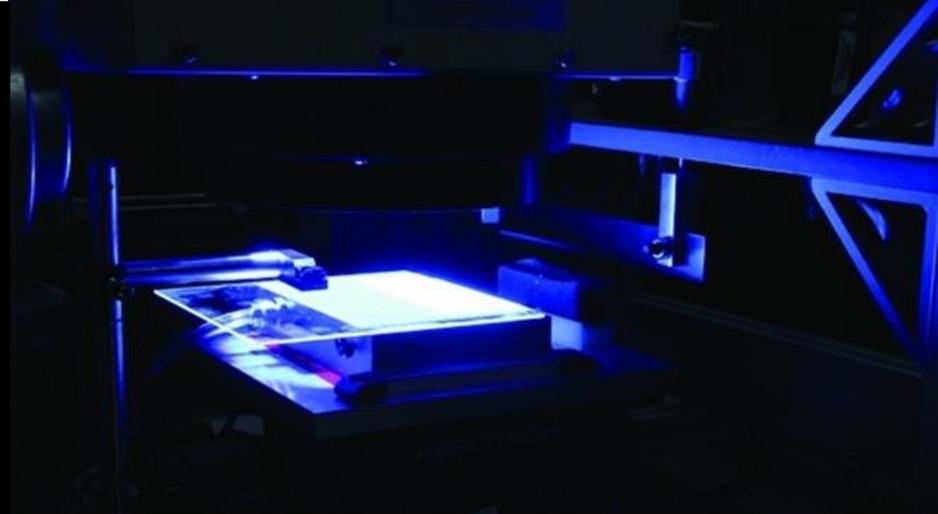
Space-Based Platform

- 3D Print Tech Demo
- Additive Manufacturing Facility
- On-demand Parts Catalogue
- Recycling Demo
- Printable Electronics Demo
- In-space Metals Demo
- **AM Propulsion Systems**
 - RS-25
 - Upper Stage Engine
- **Habitat Systems**

Planetary Surfaces Platform

- Additive Construction Technologies
- Regolith Materials - Feedstock
- **AM In Space Propulsion Systems**
 - Upper Stage
 - Orbiters
 - Landers
- **Habitat Systems**





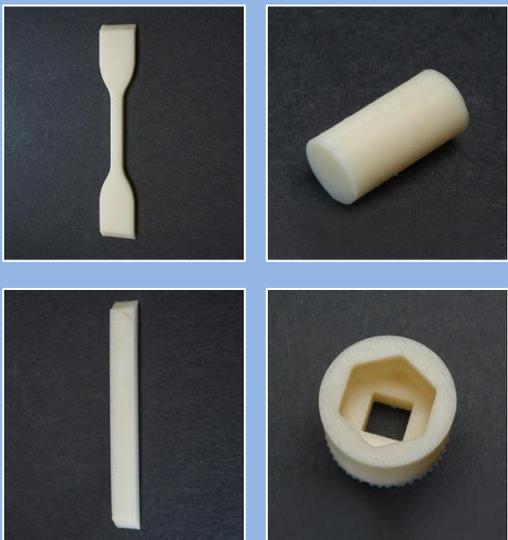
Additive Manufacturing

at Marshall Space Flight Center

In Space Manufacturing Initiative

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Mechanical Property Test Articles



Functional Tools



Printer Performance Capability



1.

Understanding how to manufacture items in space ([3-D Printing](#))



As crews head to Mars, there may be items that are unanticipated or that break during the mission. Having the ability to manufacture new objects on demand while in space will greatly benefit missions. The 3-D Printing in Zero-G Technology Demonstration validates that a 3-D printer works normally in space. This is the first step towards establishing an on-demand machine shop in space, which is a critical enabling component for crewed missions to deep space.

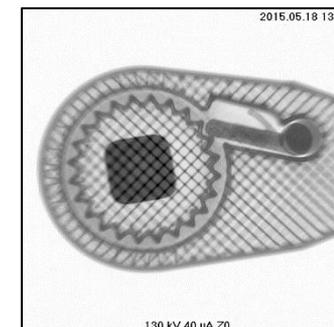
3D Printer International Space Station Technology Demonstration

- The 3D Printer Technology Demonstration flight experiment launched on SpaceX-4 and was installed in the Microgravity Science Glovebox
- Printed 21 engineering test articles from ABS feedstock. The printer functioned nominally.
- 3D Print of a ratchet tool demonstrated on-demand capability by uplinking a part file that was not pre-loaded to the 3D Printer. *Part was designed, approved for uplink/printing, and printed on-orbit within a one week span.*
- The first flight samples were received at MSFC on 3/17/15
- All specimens have undergone photographic inspection, structured light scanning, CT, and 2D Xray evaluation. Mechanical test coupons from the flight experiment have completed destructive testing. All testing has been completed.

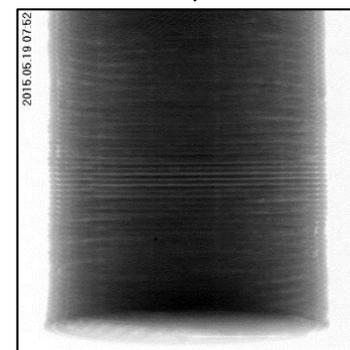
Testing and analysis results will be presented as part of a technical interchange meeting on December 2-3, 2015.



3D Printer Installed in MSG on ISS



Ratchet, Internal Mechanism (flight)



Compression Coupon (flight)

Material Characterization Database Development

- Objective: Characterize microgravity effects on printed parts and resulting mechanical properties Develop design-level database for microgravity applications.
- Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS.
- All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)

Compression Testing of Mechanical Flight Sample 7/21/15



On-demand ISM Utilization Catalogue Development

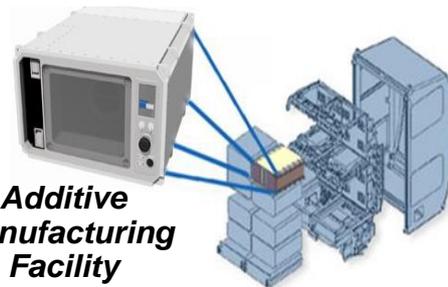
- Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization.
- Joint effort between MSFC AM M&P experts, space system designers, and JSC ISS Crew Tools Office
- First parts are in design and ground test process.



ISM Printed Part for Ground Feasibility Testing

AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space

- Commercial printer for use on ISS
- Incorporates lessons learned from 3D Printer ISS Tech Demo
- Expanded materials capabilities: ABS, ULTEM, PEEK
- Anticipated launch late CY2015



Additive Manufacturing Facility

In-space Recycler ISS Tech Demonstration Development (SBIR 2014)

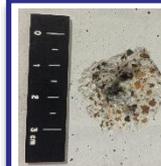
- Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
- Phase I recycler developments completed by Made In Space and Tethers Unlimited.
- Phase II SBIR (2014) awarded to Tethers Unlimited for the In-space Recycler for proposed ISS Technology Demonstration in FY2017.



Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

Launch Packaging Recycling Phase I SBIR (2015)

- Objective: Recycle launch packaging materials into feedstock to help close logistics loop (3 proposals selected for award).



Martian Concrete Ballistics Test Article

In-space Printable Electronics Technology Development

- Collaborating with Xerox Palo Alto Research Center (PARC), and NASA Ames Research Center, on Printable Electronics technologies developed at MSFC and Xerox PARC.
- Roadmap developed targeting ISS technology demonstration.



Printable Electronics

ACME - Additive Construction by Mobile Emplacement (STMD GCD)

- Joint initiative with the U. S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Automated Construction of Expeditionary Structures (ACES) Project
- Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials and minimum number of personnel.



Concept of ATHLETE-based autonomous additive construction system on extraterrestrial surface

Earth-based



Pre-2012

- Ground & Parabolic centric:*
- Multiple FDM Zero-G parabolic flights
 - Trade/System Studies for Metals
 - Ground-based Printable Electronics/Spacecraft
 - Verification & Certification Processes under development
 - Materials Database
 - Cubesat Design & Development

International Space Station



3D Print Tech Demo

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**



Plastic Printing Demo	Recycler SmallSats	Metal Printing
Add Mfctr. Facility	Printable Electronics	Self-repair/replicate External In-space Mfctr

2015

2016

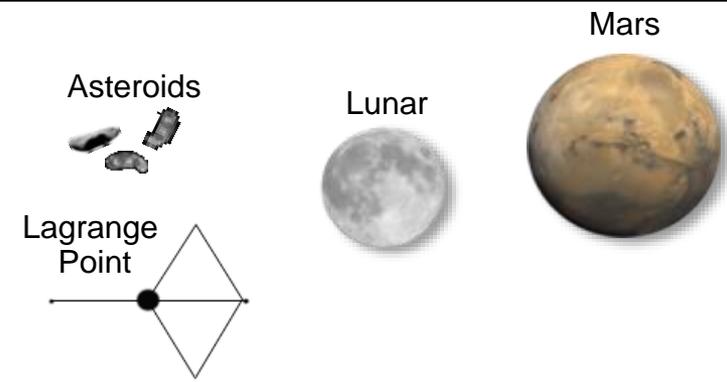
2017

2018

- **3D Print Tech Demo**
- **Future Engineer Challenge**
- **Utilization Catalogue**
- **ISM Verification & Cert Process Development**
- **Add. Mfctr. Facility (AMF)**
- **In-space Recycler SBIR**
- **In-space Material Database**
- **External In-space 3D Printing**
- **Autonomous Processes**
- **Additive In-space Repair**

- ISS: Utilization/Facility Focus**
- In-space Recycler Demo
 - Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
 - Printable Electronics Tech Demo
 - Synthetic Biology Demo
 - Metal Demo Options

Exploration



2020-25

2025

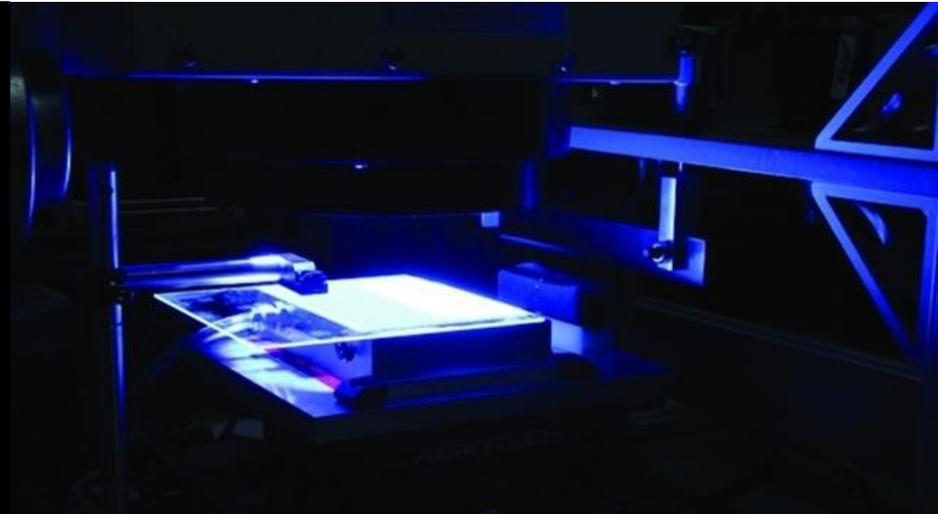
2030 - 40

- Lunar, Lagrange FabLabs*
- Initial Robotic/Remote Missions
 - Provision some feedstock
 - Evolve to utilizing in situ materials (natural resources, synthetic biology)
 - Product: Ability to produce multiple spares, parts, tools, etc. "living off the land"
 - Autonomous final milling to specification

- Planetary Surfaces Points Fab*
- Transport vehicle and sites would need Fab capability
 - Additive Construction

- Mars Multi-Material Fab Lab*
- Utilize in situ resources for feedstock
 - Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
 - Product: Fab Lab providing self-sustainment at remote destination

ISS Technology Demonstrations are Key in 'Bridging' Technology Development to Full Implementation of this Critical Exploration Technology.



Additive Manufacturing

at Marshall Space Flight Center

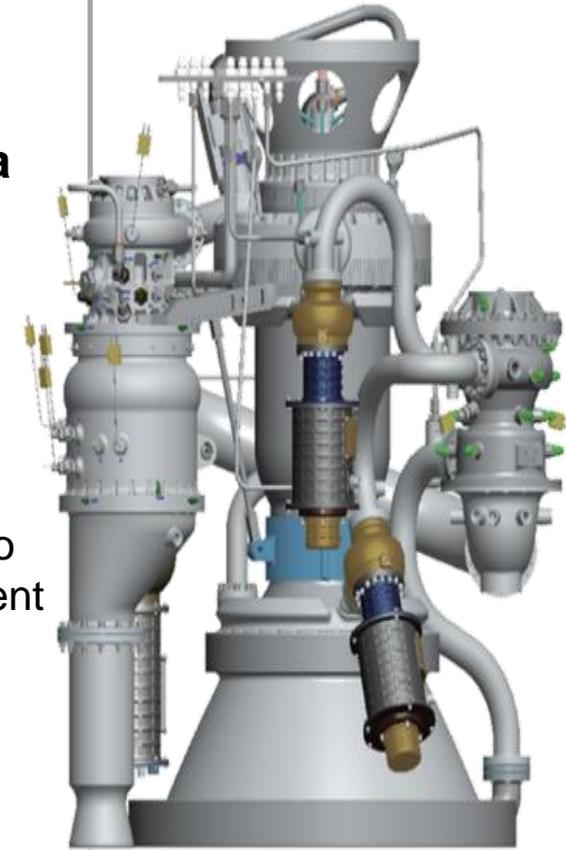
Advanced Manufacturing Demonstrator - Liquid Propulsion System
and Low-Cost Upper Stage Propulsion Project

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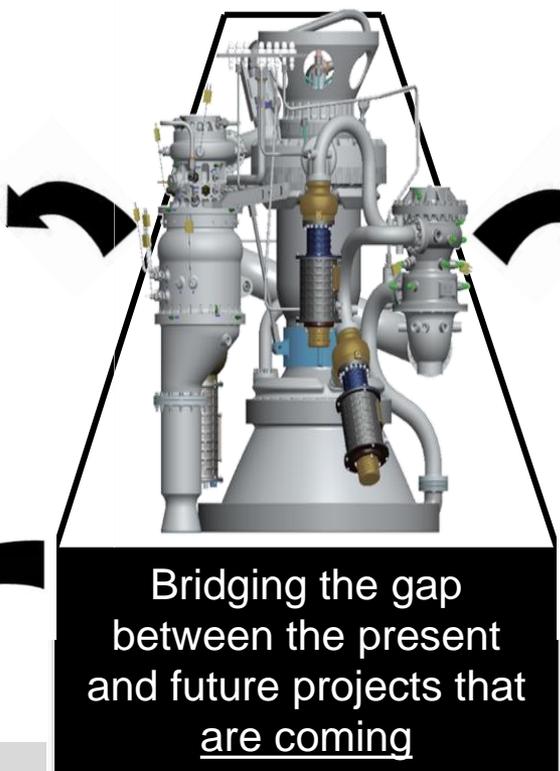
Project Objectives

- **Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.**
 - Prototype engine in less than 2.5 years
 - Additive manufacturing to reduce part cost, fabrication time, and overall part count
 - Lean Development approach
 - Focus on fundamental/quick turn around analysis to reduce labor time and cost to get to first development unit
 - Get hardware into test fast so that test data can be used to influence/refine the design
- **Advance the TRL of additive manufactured parts through component and engine testing**
- **Develop a cost effective prototype engine whose basic design can be used as the first development unit for an in space propulsion class engine.**



Defining the Development Philosophy of the Future

- Integrating Design with Manufacturing
- 3D Design Models and Simulations Increase Producibility
- Transforming Manual to Automated Manufacturing
- Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles



Building Experience "Smart Buyer" to enable Commercial Partners



Building Foundational Industrial Base



Enabling & Developing Revolutionary Technology



Bridging the gap between the present and future projects that are coming

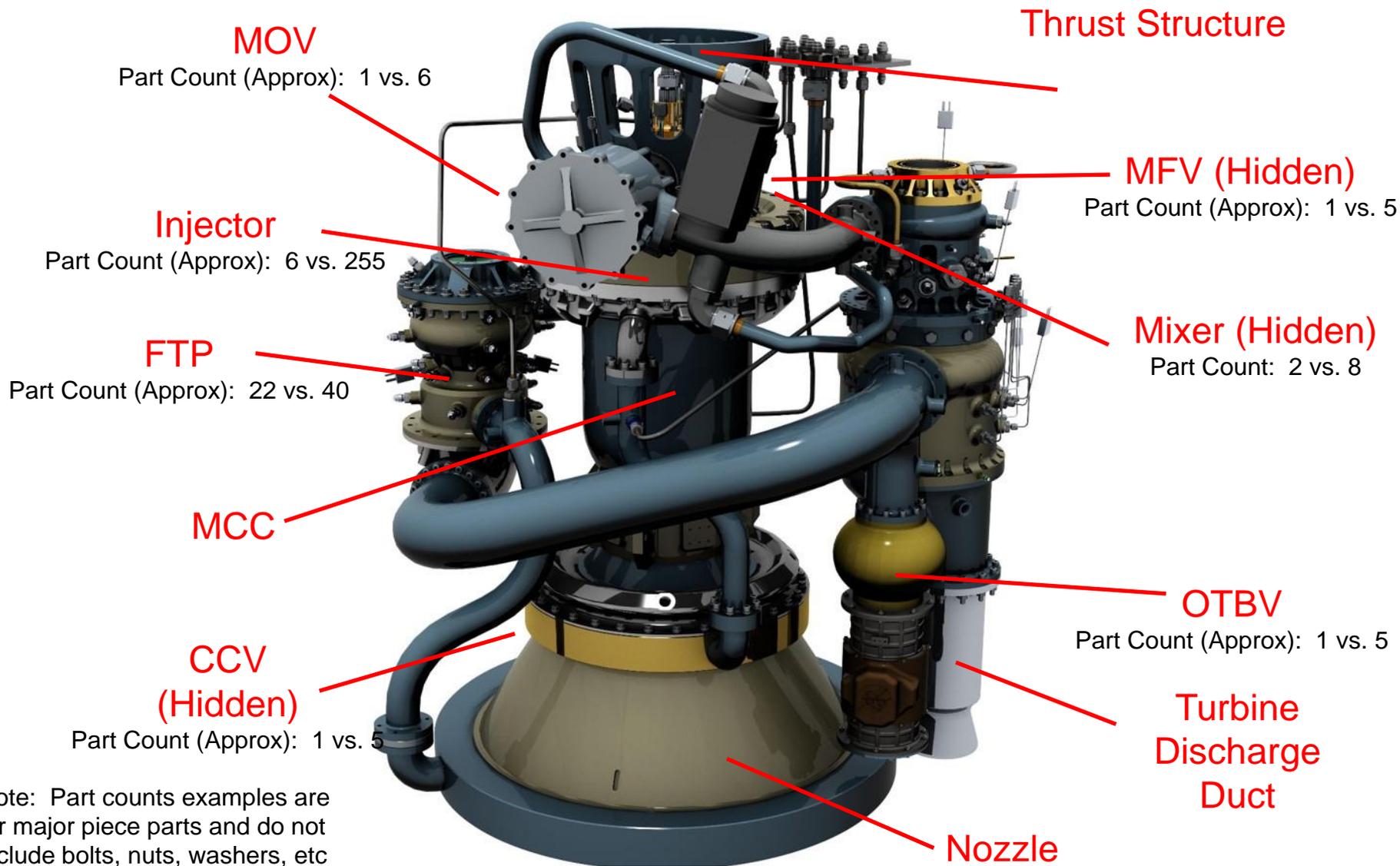
Transferring "Open Rights" SLM Material Property Data & Technology to U.S. Industry

State of the Art for Typical Engine Developments

Prototype Additive Engine

- | | |
|--|--|
| <ul style="list-style-type: none"> • DDT&E Time <ul style="list-style-type: none"> – 7-10 years | <ul style="list-style-type: none"> • DDT&E Time <ul style="list-style-type: none"> – 2-4 years |
| <ul style="list-style-type: none"> • Hardware Lead Times <ul style="list-style-type: none"> – 3-6 Years | <ul style="list-style-type: none"> • Hardware Lead Times <ul style="list-style-type: none"> – 6 Months |
| <ul style="list-style-type: none"> • Testing <ul style="list-style-type: none"> – Late in the DDT&E cycle | <ul style="list-style-type: none"> • Testing <ul style="list-style-type: none"> – Testing occurs early in the DDT&E cycle |
| <ul style="list-style-type: none"> • Engine Cost <ul style="list-style-type: none"> – \$20 - \$50 Million | <ul style="list-style-type: none"> • Prototype Cost <ul style="list-style-type: none"> – \$3-5 Million |
| <ul style="list-style-type: none"> • Applicability <ul style="list-style-type: none"> – Design for particular mission by a particular contractor – Often proprietary | <ul style="list-style-type: none"> • Applicability <ul style="list-style-type: none"> – Provide relevant data to multiple customers (SLS, Commercial partners, other government agencies) – Flexible test bed configuration can accommodate other's hardware / design concepts |

Reduction in Parts Count for Major Hardware



Advanced Manufacturing Demonstrator Test Stand

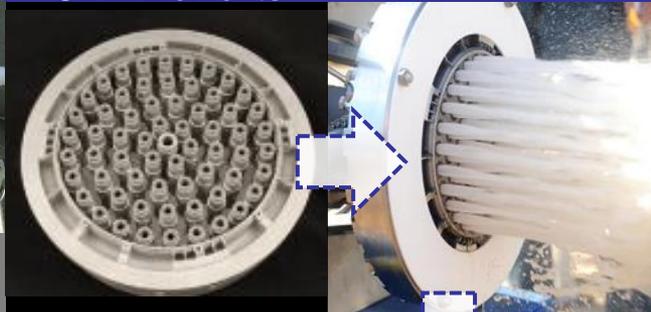


LCUSP MCC Liner

Main Fuel Valve Cryo Test

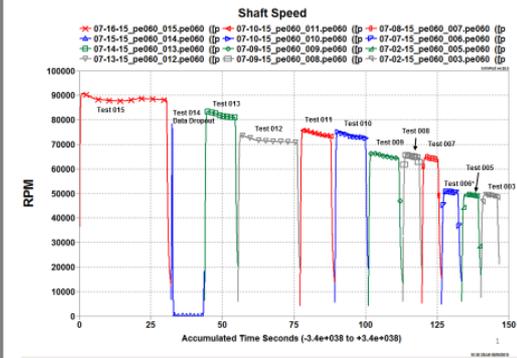
Fuel Scale Injector Swirl Elements

Full Scale Injector Water Flow



Sub-scale Injector Test

Test Data – Shaft Speed



Fuel Turbopump Performance Test in Hydrogen

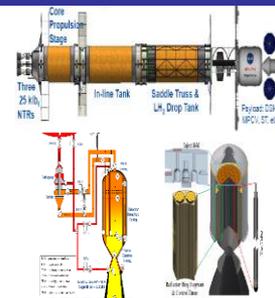


Advanced Manufacturing Demonstrator (AMD)

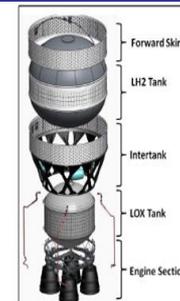
Investment directly benefits prototype engine development and indirectly enables and facilitates technology across multiple current and future activities for NASA and industry.



Methane Lander

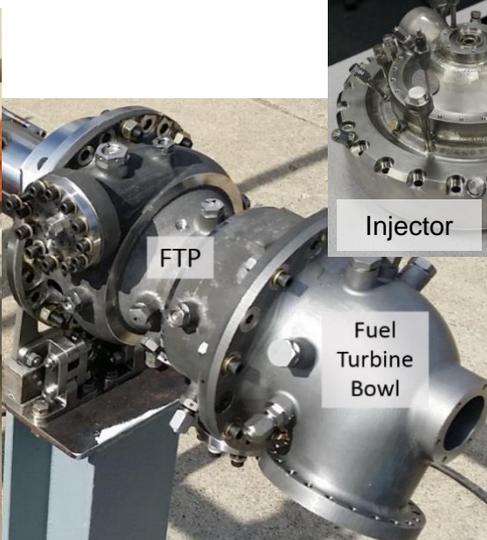
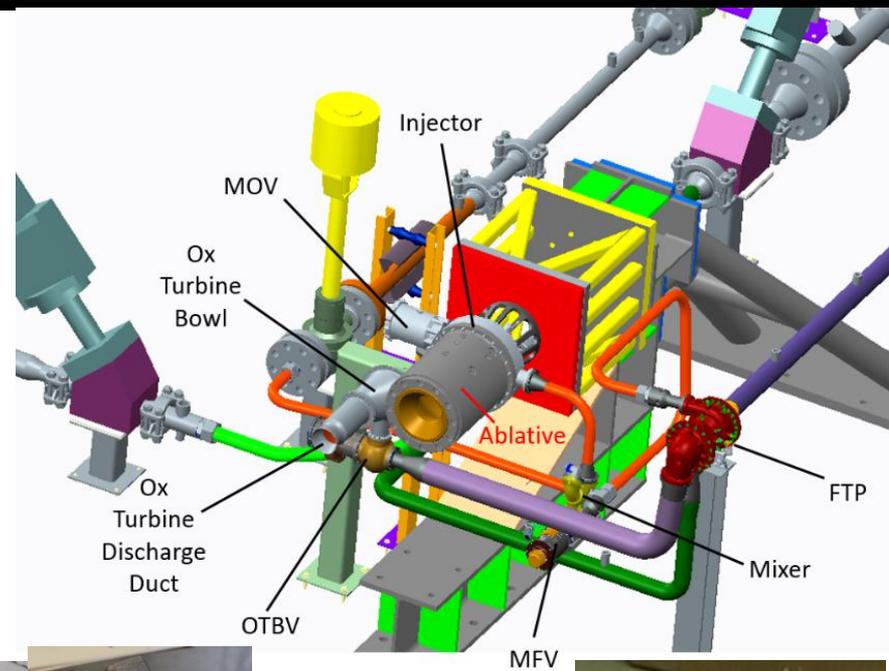


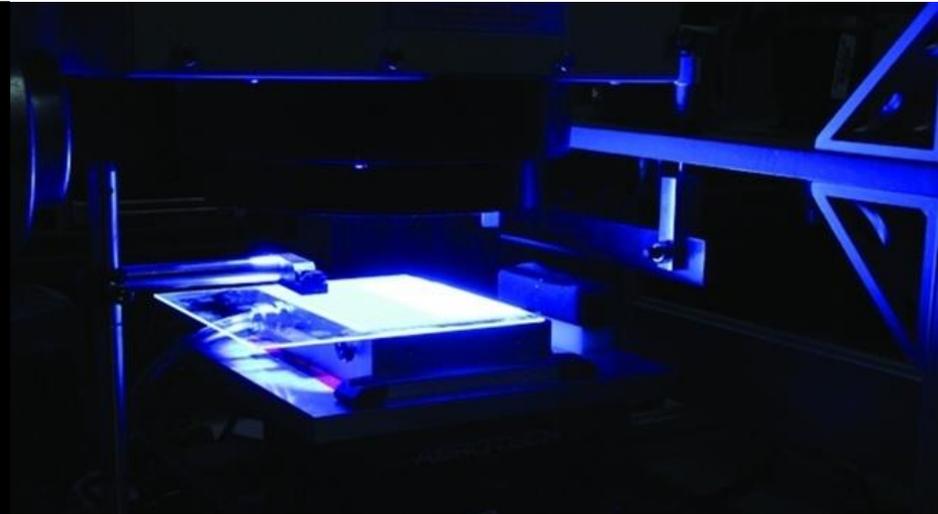
Nuclear Thermal Propulsion (NTP)



Exploration Upper Stage (EUS)

- ❖ Demonstration of Essential Technologies in Relevant Environment to Validate 3-D Printed Parts
- ❖ Planned for September 2015
- ❖ Design and manufacture LOX turbopump in FY16





Additive Manufacturing

at Marshall Space Flight Center

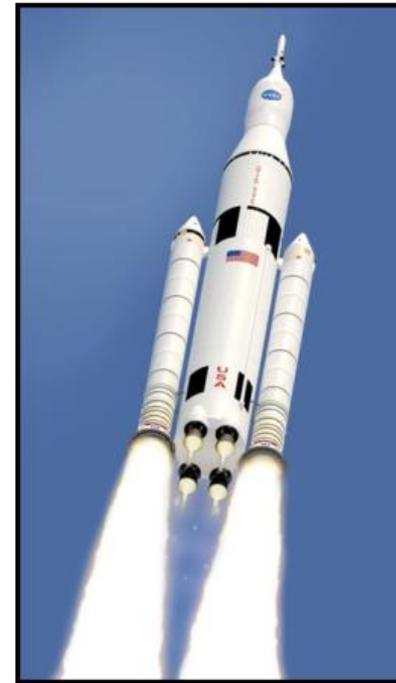
RS-25 Affordability Initiative – Additive Manufacturing's Increasing Role

POC: Steve Wofford
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Improve producibility while maintaining reliability



SSME – Reusable, high performance & reliable



RS-25 – Expendable, affordable & reliable

- **Comprehensive affordability review of complete engine system conducted**
- **Focus efforts on affordability with established change control processes and rigor**
 - Avoid large development program or clean sheet design risks
 - Challenge entrenched thinking and encourage innovation
 - Tailor requirements to meet program goals
- **New fabrication technology including Additive Manufacturing to improve workflow and reduce cost**
- **Aerojet Rocketdyne (AR), MSFC and Industry have demonstrated component functionality and cost savings with Additive Manufacturing (AM)**
 - AR leading development of Alloy 625
 - MSFC leading development of Alloy 718



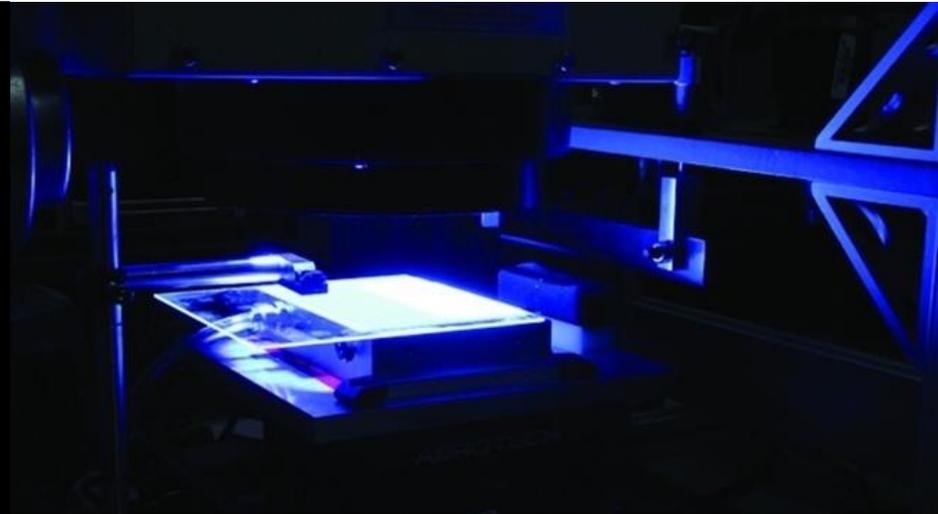
33% Reduction in Engine Cost

35 AM Opportunities Identified for RS-25

- **Incorporate modern inspection technology to improve efficiency**

**>700 Welds Eliminated
>700 Parts Eliminated**

- **Process Failure Modes and Effects Analysis – What are the credible failure modes for the process?**
- **Process Control – How do we ensure an AM process to be repeatable, reliable, and in-control?**
- **Non Destructive Evaluation - How will AM parts be inspected for critical defects?**
- **Acceptance Testing – What part-specific acceptance testing is needed to ensure part integrity?**
- **Technology Evolution – How do we adapt to next-generation machines and processes?**



Additive Manufacturing

at Marshall Space Flight Center

Draft Certification Approach for Additively Manufactured Rocket Engine Parts

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- **Opportunity**
 - Additive Manufacturing (AM) offers revolutionary opportunities in mechanical design innovation, cost savings, and schedule reduction

- **Risk**
 - Process sensitivity :: unknown failure modes
 - Lack of governing requirements
 - Rapidly evolving technology
 - Too easy, too cheap = ubiquitous, lack of rigor
 - AM related failure tarnishes the technology

- **Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities wisely**

- **Typical scenario used to control critical processes**
 - Broad Agency-level standards provide requirements
 - NASA-STD-6016 Materials
 - NASA-STD-5012 Propulsion Structures
 - NASA-STD-5019 Fracture Control
 - *Which call* process or quality standard controls product, for example:
 - AWS D17.1 Fusion Welding for Aerospace Applications
 - SAE AMS 2175 Classification and Inspection of Castings
 - SAE AMS 4985 Ti-6-4 Investment Castings
 - *Which call* considerable collections of “Applicable Documents”
- **Additive manufacturing standards currently very limited**
 - Lacking standardization is a universal, industry-wide issue, not just NASA
 - Mainly ASTM, Committee F42 on Additive Manufacturing
 - F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718)with Powder Bed Fusion
 - F2924 for Ti-6-4, F3001 for Ti-6-4ELI, F3056 for In625
 - Other Standards organizations in planning
 - SAE AMS, AWS
- **NASA required to develop government requirements to balance AM opportunities and risks.**

Develop a Center-level (MSFC) requirement

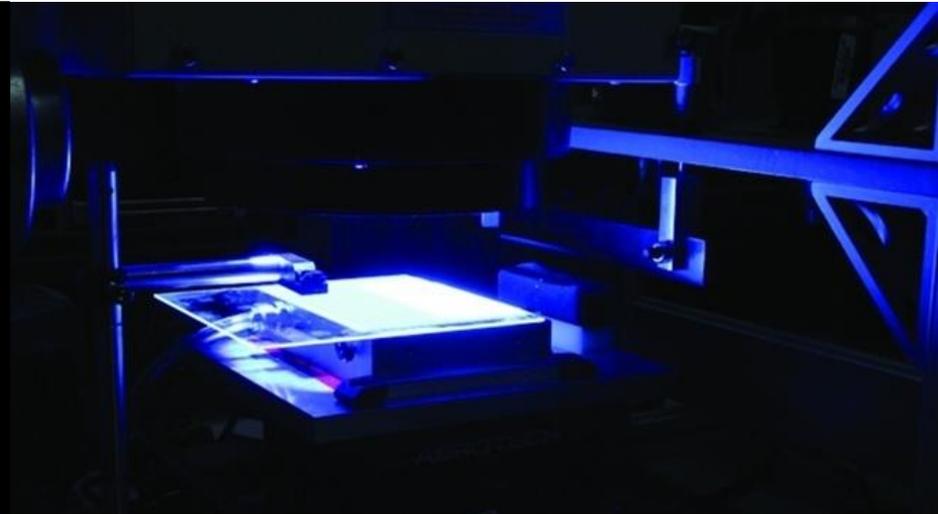
- Allows for more timely release (July 2015)
- Review circle much wider than common
 - Centers
 - NESC (materials, structures, NDE, Reliability)
 - Partners (Aerojet-Rocketdyne, SpaceX, Lockheed Martin)
 - Industry (GE, Honeywell)
 - Certifying Agencies (FAA, USAF)

Key topics in the draft AM requirements

- ***Tailoring***
- Governing standards
- AM Design
- ***Part Classification***
- Structural Assessment
- Fracture Control
- Qualification Testing
- Part Development Plans
- ***Process Controls***
- ***Material Properties***
- Finishing, Cleaning, Repair Allowances
- Part Inspection and Acceptance

- **Available requirements will not mitigate AM part risk to an equivalent level as other processes for some time to come!**
- **Known Unknowns needing investment:**
 - Unknown failure modes :: limited process history
 - Open loop process, needs closure or meaningful feedback
 - Feedstock specifications and controls
 - Thermal processing
 - Process parameter sensitivity
 - Mechanical properties
 - Part Cleaning
 - Welding of AM materials
 - AM Surface improvement strategies
 - NDE of complex AM parts
 - Electronic model data controls
 - Equipment faults, modes of failure
 - Machine calibration / maintenance
 - Vendor quality approvals

Knowledge gaps exist in the basic understanding of AM Materials and Processes, creating potential for risk to certification of critical AM Hardware.



Additive Manufacturing

at Marshall Space Flight Center

Additive Manufacturing Structural Integrity Initiative (AMSII)

*Ensuring the Structural Integrity of Inconel 718 Rocket Propulsion
Components built with Powder Bed Fusion Technology*

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Goal

- Develop powder bed fusion (PBF) as a reliable and routine alternative to traditional manufacturing methods for human-rated flight hardware.

Objectives

- Mature a jointly-defined, resource-loaded technology project to close the knowledge gaps that underpin our drafted AM requirement document.
 - Emphasis on activities required for flight certification.
 - Initial focus on Inconel 718 produced with powder bed fusion technology.
- Develop an inter-center team to pool knowledge and provide peer review of AM technology development and activities.
- Mature NASA-wide or local requirement document(s) in order to enhance standardization of AM for flight hardware.

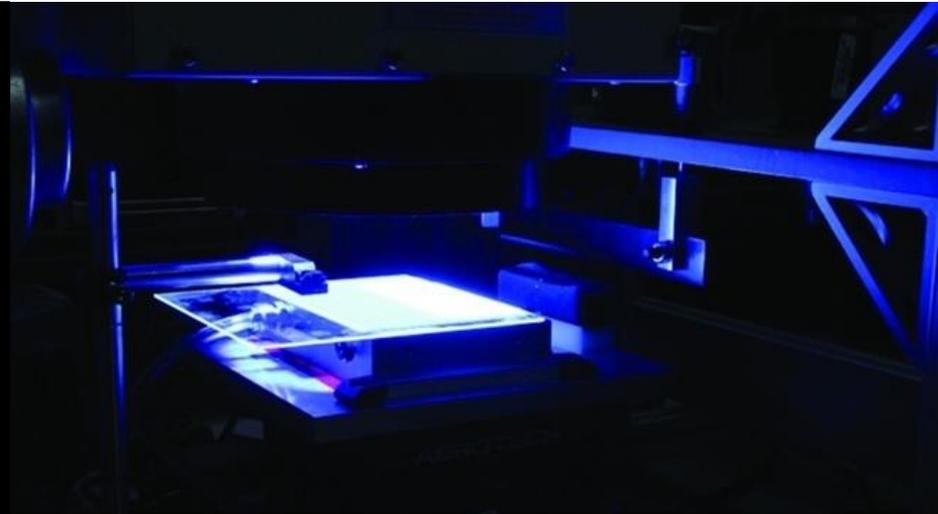


Build the standard level of information on AM powder bed fusion processes that is required for certification of any new critical process used for aerospace applications. Better understanding of controlling process parameters and process failure modes will be achieved through completion of this study.

- Certification Requirements – **MSFC**/JSC/KSC (committee) **Objective:** Develop an Agency-wide accepted practice for the certification of AM processes for aerospace hardware.
- 1. Powder Influence – **GRC**/LaRC/MSFC **Objective:** Understand how basic powder feedstock characteristics influence a PBF part's physical, mechanical, and surface properties.
- 2. Build Interactions – **MSFC**/GRC/JSC/KSC/LaRC **Objective:** Use DOEs to understand how basic AM build factors influence part properties. (Answers how we declare the PBF process acceptable & in-control; e.g. microstructural criteria, density criteria, laser/power effects, process FMEA, mitigation of process failure modes)
- 3. Characteristic Defects – **LaRC**/GRC/JSC/KSC/MSFC **Objective:** Identify, catalog, and reproduce defects characteristic of the AM process.
- 4. Thermal Processing – **GRC**/LaRC/MSFC **Objective:** Establish an understanding of how post-build thermal treatments affect build quality, microstructural evolution, and mechanical properties.
- 5. Surface Improvement – **LaRC**/MSFC **Objective:** Understand how as-built and improved AM surface texture influence part performance and fatigue life.
- 6. Characterization in Environment – **MSFC**/GRC/KSC/JSC/LaRC **Objective:** Understand mechanical behavior of AM Inconel 718 in representative aerospace environments.
- 7. Design Engineering – **MSFC** **Objective:** Demonstrate the certification process for AM propulsion components. Increase TRL of propulsion components through testing in operational environment.

Related Task: NASA NDE Working Group Additive Manufacturing Proposed Tasks – Various Centers **Objective:** Assessment of NDE Capability for AM parts and creation of NDE standards and models. (sponsored by OSMA)

Project designed to leverage Centers' critical skills, knowledge, and expertise.



Additive Manufacturing

Snapshot of Activities Around the Agency

Ames Research Center – Jessica Koehne

Glenn Research Center – Michael Meyer, Bob Carter

Goddard Space Flight Center – Peter Hughes, Ted Swanson, Matt Showalter

Jet Propulsion Laboratory – Kendra Short

Johnson Space Center – Michael Waid

Kennedy Space Center – Jack Fox

Langley Research Center – Rob Mueller, Rob Hafley, Karen Taminger

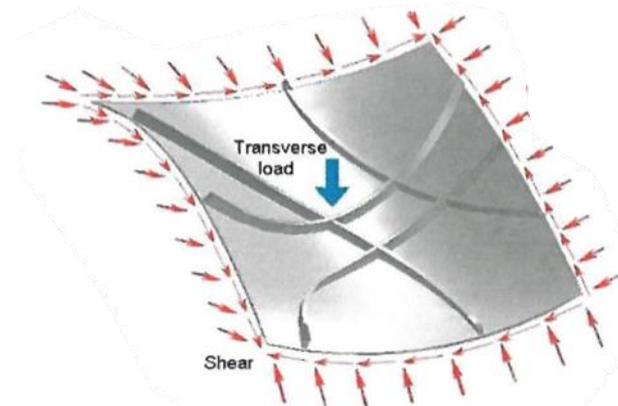
Marshall Space Flight Center – Kristin Morgan, Niki Werkheiser, Janet Salverson

University of Southern California – Berok Khoshnevis (CCI)

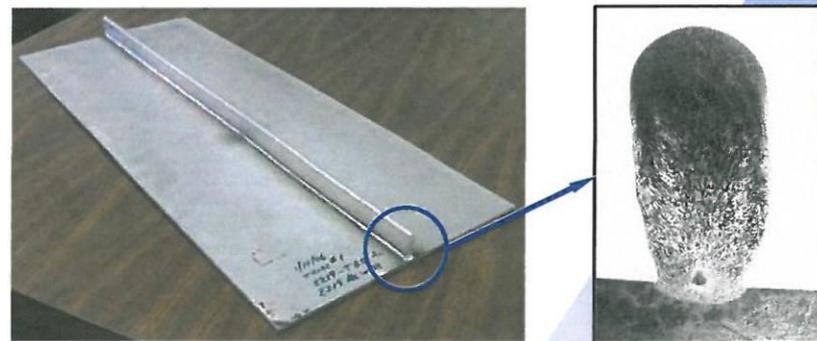


Aeronautics Applications

- Engineered materials coupled with tailored structural design enable reduced weight and improved performance for future aircraft fuselage and wing structures
- Multi-objective optimization:
 - Structural load path
 - Acoustic transmission
 - Durability and damage tolerance
 - Minimum weight
 - Materials functionally graded to satisfy local design constraints
- Additive manufacturing using new alloys enables unitized structure with functionally graded, curved stiffeners
- Weight reduction by combined tailoring structural design and designer materials



Design optimization tools integrate curvilinear stiffener and functionally graded elements into structural design



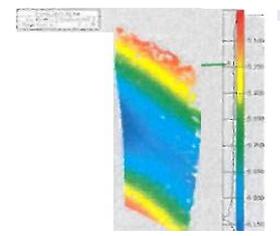
High toughness alloy at stiffener base for damage tolerance, transitioning to metal matrix composite for increased stiffness and acoustic damping

- Objective: Conduct the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable fully non-metallic gas turbine engines.
- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and Ceramic matrix composites.
 - Fabricate prototype components and test in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost
- Focusing on high temperature and fiber reinforced polymer composites fabricated using FDM, and fundamental development of high temperature ceramics / CMC's using binder jet process

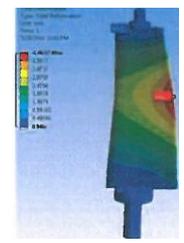
A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing



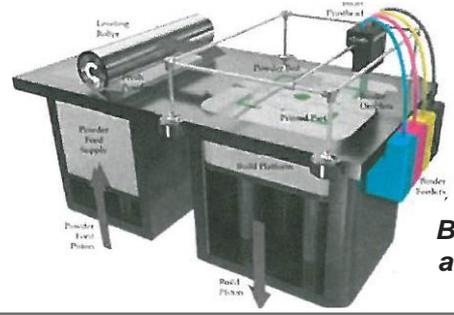
Polymer Vane Configuration in Cascade wind tunnel Rig



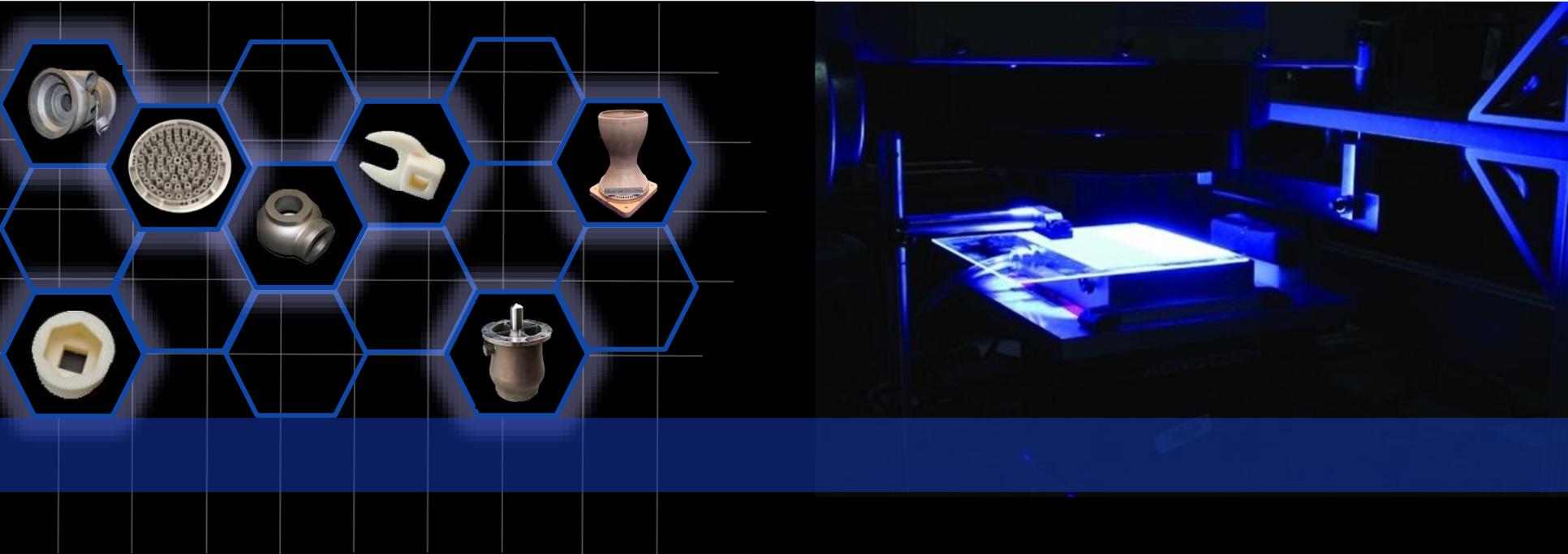
Digital Image Correlation Measurements



Finite Element Analysis

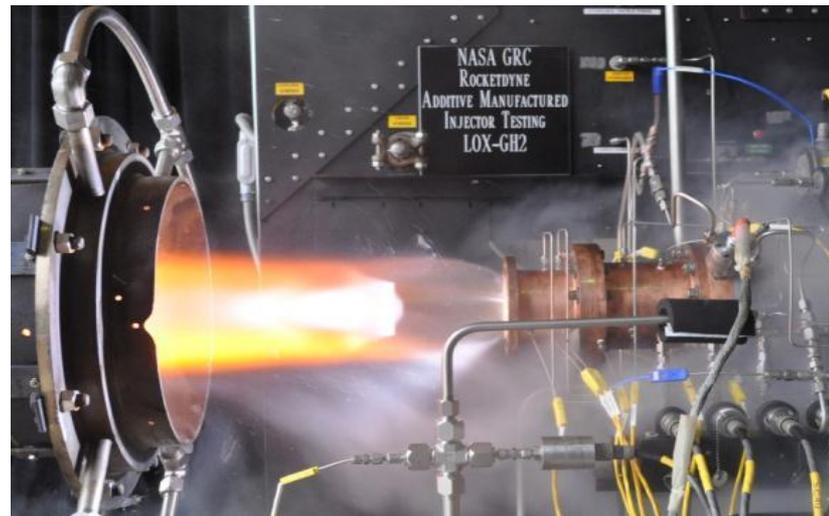


Binder jet process was adapted for SiC fabrication

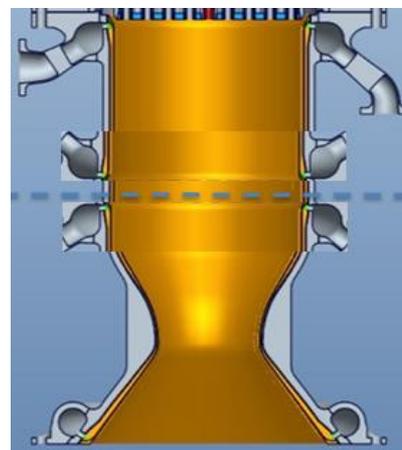


“FOR Space” Additive Manufacturing

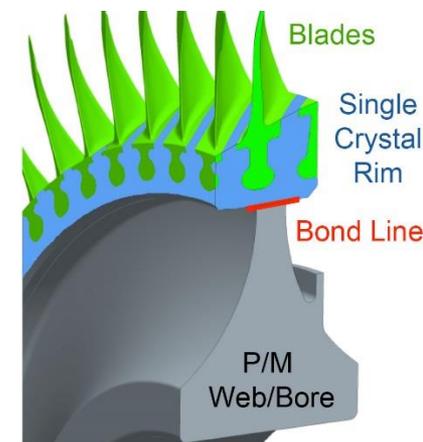
- GRC and Aerojet Rocketdyne tested an additively manufactured injector in 2013 under the Manufacturing Innovation Project (MIP) and Advanced Manufacturing Technologies (AMT) Project.
- GRC, LaRC, and MSFC LCUSP Team building on success of MIP and AMT AMD-LPS projects to develop and hot fire test additively manufactured GRCop 84 thrust chamber assembly
- RL10 Additive Manufacturing Study (RAMS) task order between GRC and Aerojet-Rocketdyne sponsored by USAF.
- GRC, AFRL, MSFC Additive Manufacturing of Hybrid Turbomachinery Disk



GRC and Aerojet Rocketdyne test



CAD sketch of rocket nozzle



Hybrid Disk Concept

MSFC

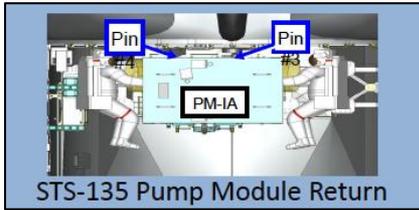
- AM techniques can create extremely fine internal geometries that are difficult to achieve with subtractive manufacturing methods.



ISS Urine Processor Assembly

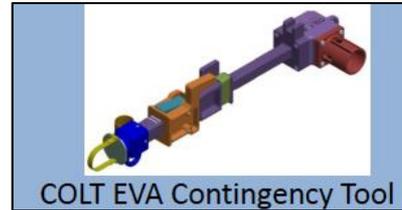


Air Filter/Scrubbers



STS-135 Pump Module Return

ISS EVA Tool Fabrication & Certification Demo

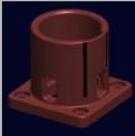


COLT EVA Contingency Tool

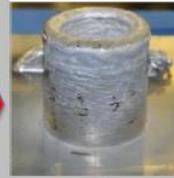
JSC

- ISS Tool Design for Manufacturability and Processing
- Structural Integrity Verification
 - Material Properties
 - Non-destructive Evaluation
 - Structural Analysis and Testing

Fabrication


Model


Deposition

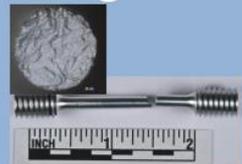

Pre-form

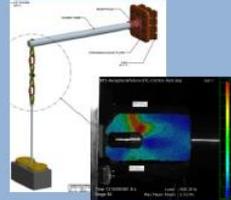

Heat Treat

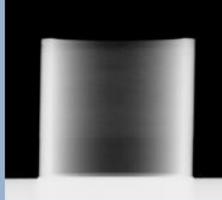

Finished Part


Assembly

Testing

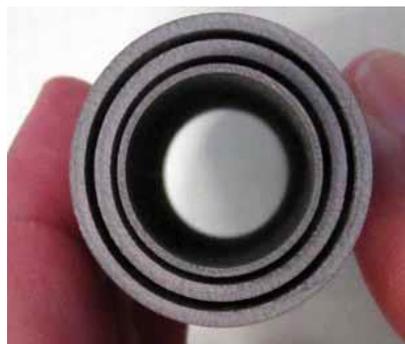

Coupon Testing


Part Testing

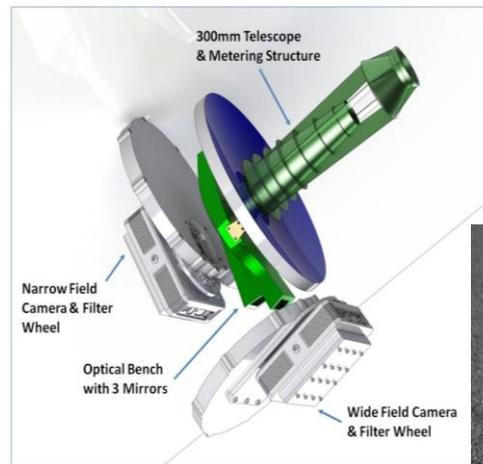

Inspection


Metallography

- GSFC’s first Additive Manufacturing (AM) part for instrument prototype/possible flight use (FY12) - Titanium tube - in a tube – in a tube for cryo thermal switch for ASTRO-H
- First to fly AM component in space (FY13) – battery case on suborbital sounding rocket mission
- Miniaturizing telescopes: Utilize new Direct Metal Laser Sintering (DMLS) to produce dimensionally stable integrated instrument structures at lower cost
- Unitary core-and-face-sheet optical bench material
 - Features tailored alloy composition to achieve desired coefficient of thermal expansion
- Efficient radiation shielding through Direct Metal Laser Sintering:
 - Develop a method for mitigating risk due to total ionizing dose (TID) using direct metal laser sintering (DMLS) and the commercially-available Monte-Carlo particle transport code, NOVICE to enable otherwise difficult to fabricate component-level shielding

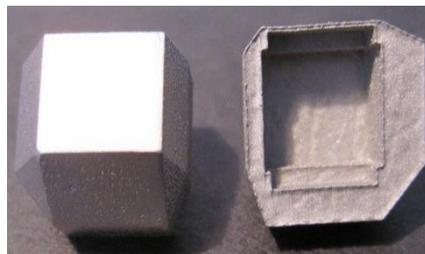
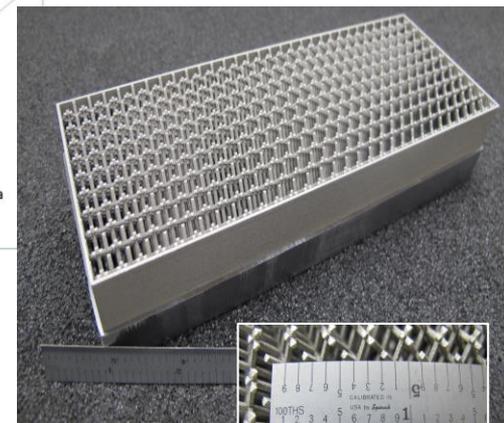


Battery Case

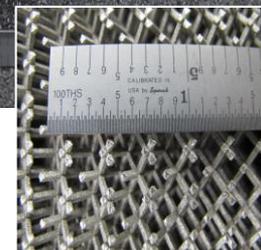


0.3m Telescope via DMLS

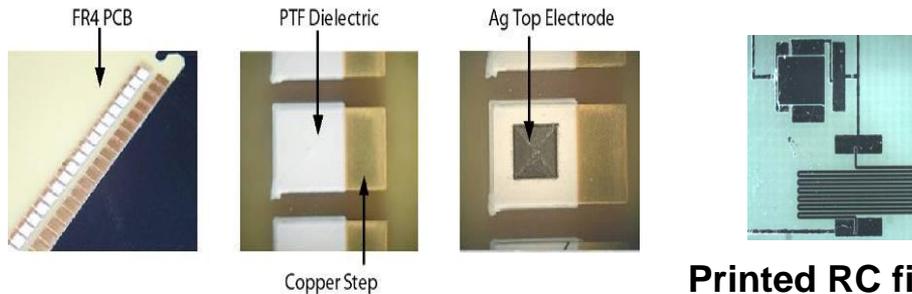
Optical bench core material sample



DMLS printed shield



- Aerosol jet printing of various circuit building blocks: crossovers, resistors, capacitors, chip attachments, EMI shielding.



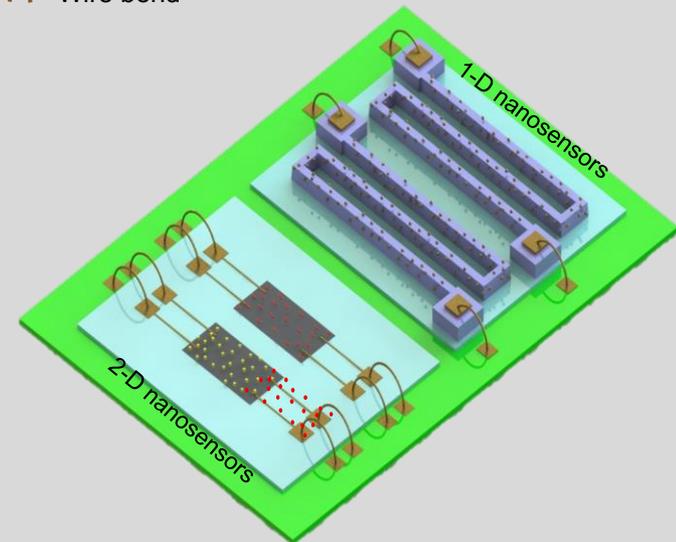
Printed RC filter

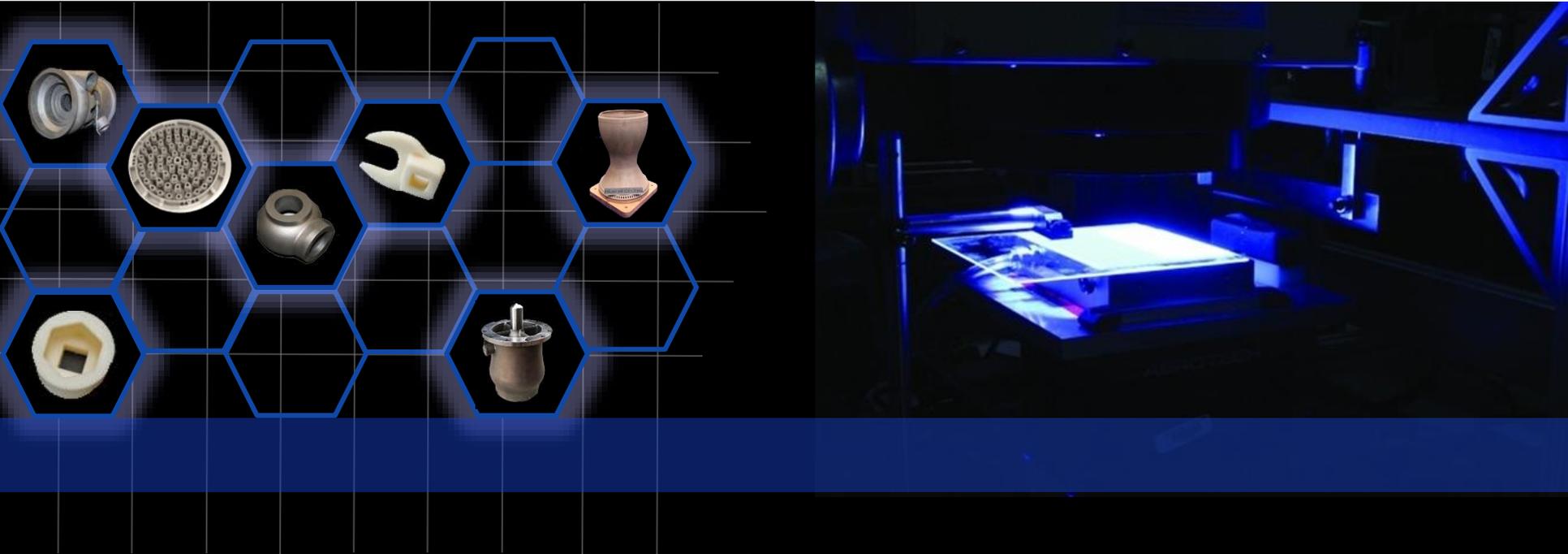
Multi-layer deposition, Polyimide dielectric and Ag deposited onto Cu pads to make a simple capacitor

- Nanosensors printed directly on a daughter board for chemical detection
- Super-black nanotechnology coating: Enable Spacecraft instruments to be more sensitive without enlarging their size. Demonstrated growth of a uniform layer of carbon nanotubes through the use of Atomic Layer Deposition.

Printed Nanosensor

- Graphene
- Functional groups for selectivity
- Nanowires
- Metal cluster for selectivity
- Printed Circuit Board
- Contact pad
- Metal lead
- Wire bond





“IN Space” Additive Manufacturing

Printable Electronics

- ARC/MSFC/JPL: Develop in-space manufacturing capabilities to produce functional electronic and photonic component on demand.

Printed Electronics for In-Space Manufacturing

(a) (b) (c) (d) (e)

inkjet printing (a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n) (o) (p) (q) (r) (s) (t) (u) (v) (w) (x) (y) (z) (aa) (ab) (ac) (ad) (ae) (af) (ag) (ah) (ai) (aj) (ak) (al) (am) (an) (ao) (ap) (aq) (ar) (as) (at) (au) (av) (aw) (ax) (ay) (az) (ba) (bb) (bc) (bd) (be) (bf) (bg) (bh) (bi) (bj) (bk) (bl) (bm) (bn) (bo) (bp) (bq) (br) (bs) (bt) (bu) (bv) (bw) (bx) (by) (bz) (ca) (cb) (cc) (cd) (ce) (cf) (cg) (ch) (ci) (cj) (ck) (cl) (cm) (cn) (co) (cp) (cq) (cr) (cs) (ct) (cu) (cv) (cw) (cx) (cy) (cz) (da) (db) (dc) (dd) (de) (df) (dg) (dh) (di) (dj) (dk) (dl) (dm) (dn) (do) (dp) (dq) (dr) (ds) (dt) (du) (dv) (dw) (dx) (dy) (dz) (ea) (eb) (ec) (ed) (ee) (ef) (eg) (eh) (ei) (ej) (ek) (el) (em) (en) (eo) (ep) (eq) (er) (es) (et) (eu) (ev) (ew) (ex) (ey) (ez) (fa) (fb) (fc) (fd) (fe) (ff) (fg) (fh) (fi) (fj) (fk) (fl) (fm) (fn) (fo) (fp) (fq) (fr) (fs) (ft) (fu) (fv) (fw) (fx) (fy) (fz) (ga) (gb) (gc) (gd) (ge) (gf) (gg) (gh) (gi) (gj) (gk) (gl) (gm) (gn) (go) (gp) (gq) (gr) (gs) (gt) (gu) (gv) (gw) (gx) (gy) (gz) (ha) (hb) (hc) (hd) (he) (hf) (hg) (hh) (hi) (hj) (hk) (hl) (hm) (hn) (ho) (hp) (hq) (hr) (hs) (ht) (hu) (hv) (hw) (hx) (hy) (hz) (ia) (ib) (ic) (id) (ie) (if) (ig) (ih) (ii) (ij) (ik) (il) (im) (in) (io) (ip) (iq) (ir) (is) (it) (iu) (iv) (iw) (ix) (iy) (iz) (ja) (jb) (jc) (jd) (je) (jf) (jg) (jh) (ji) (jj) (jk) (jl) (jm) (jn) (jo) (jp) (jq) (jr) (js) (jt) (ju) (jv) (jw) (jx) (jy) (jz) (ka) (kb) (kc) (kd) (ke) (kf) (kg) (kh) (ki) (kj) (kk) (kl) (km) (kn) (ko) (kp) (kq) (kr) (ks) (kt) (ku) (kv) (kw) (kx) (ky) (kz) (la) (lb) (lc) (ld) (le) (lf) (lg) (lh) (li) (lj) (lk) (ll) (lm) (ln) (lo) (lp) (lq) (lr) (ls) (lt) (lu) (lv) (lw) (lx) (ly) (lz) (ma) (mb) (mc) (md) (me) (mf) (mg) (mh) (mi) (mj) (mk) (ml) (mm) (mn) (mo) (mp) (mq) (mr) (ms) (mt) (mu) (mv) (mw) (mx) (my) (mz) (na) (nb) (nc) (nd) (ne) (nf) (ng) (nh) (ni) (nj) (nk) (nl) (nm) (nn) (no) (np) (nq) (nr) (ns) (nt) (nu) (nv) (nw) (nx) (ny) (nz) (oa) (ob) (oc) (od) (oe) (of) (og) (oh) (oi) (oj) (ok) (ol) (om) (on) (oo) (op) (oq) (or) (os) (ot) (ou) (ov) (ow) (ox) (oy) (oz) (pa) (pb) (pc) (pd) (pe) (pf) (pg) (ph) (pi) (pj) (pk) (pl) (pm) (pn) (po) (pp) (pq) (pr) (ps) (pt) (pu) (pv) (pw) (px) (py) (pz) (qa) (qb) (qc) (qd) (qe) (qf) (qg) (qh) (qi) (qj) (qk) (ql) (qm) (qn) (qo) (qp) (qq) (qr) (qs) (qt) (qu) (qv) (qw) (qx) (qy) (qz) (ra) (rb) (rc) (rd) (re) (rf) (rg) (rh) (ri) (rj) (rk) (rl) (rm) (rn) (ro) (rp) (rq) (rr) (rs) (rt) (ru) (rv) (rw) (rx) (ry) (rz) (sa) (sb) (sc) (sd) (se) (sf) (sg) (sh) (si) (sj) (sk) (sl) (sm) (sn) (so) (sp) (sq) (sr) (ss) (st) (su) (sv) (sw) (sx) (sy) (sz) (ta) (tb) (tc) (td) (te) (tf) (tg) (th) (ti) (tj) (tk) (tl) (tm) (tn) (to) (tp) (tq) (tr) (ts) (tt) (tu) (tv) (tw) (tx) (ty) (tz) (ua) (ub) (uc) (ud) (ue) (uf) (ug) (uh) (ui) (uj) (uk) (ul) (um) (un) (uo) (up) (uq) (ur) (us) (ut) (uu) (uv) (uw) (ux) (uy) (uz) (va) (vb) (vc) (vd) (ve) (vf) (vg) (vh) (vi) (vj) (vk) (vl) (vm) (vn) (vo) (vp) (vq) (vr) (vs) (vt) (vu) (vv) (vw) (vx) (vy) (vz) (wa) (wb) (wc) (wd) (we) (wf) (wg) (wh) (wi) (wj) (wk) (wl) (wm) (wn) (wo) (wp) (wq) (wr) (ws) (wt) (wu) (wv) (ww) (wx) (wy) (wz) (xa) (xb) (xc) (xd) (xe) (xf) (xg) (xh) (xi) (xj) (xk) (xl) (xm) (xn) (xo) (xp) (xq) (xr) (xs) (xt) (xu) (xv) (xw) (xx) (xy) (xz) (ya) (yb) (yc) (yd) (ye) (yf) (yg) (yh) (yi) (yj) (yk) (yl) (ym) (yn) (yo) (yp) (yq) (yr) (ys) (yt) (yu) (yv) (yw) (yx) (yy) (yz) (za) (zb) (zc) (zd) (ze) (zf) (zg) (zh) (zi) (zj) (zk) (zl) (zm) (zn) (zo) (zp) (zq) (zr) (zs) (zt) (zu) (zv) (zw) (zx) (zy) (zz)

- Develop in-space manufacturing capabilities to produce functional electronic and photonic components on demand.
- Printable inexpensive functional electrical devices is a rapidly evolving field
 - Substrates include: plastic, glass, silicon wafer, transparent or stretchable polymer, cellulose paper, textiles
 - Various inks are being developed including: carbon nanotubes, silver, gold, copper, titanium dioxide, silicon dioxide
- Take the first step towards printing electronics on-demand in space – building block approach
 - Select, develop and characterize inks for electronics printing
 - Development and fabrication of flight suitable electronic printer
 - Demonstrate circuit blocks
- Fly a Technology Demonstration on ISS to build some functional electronic/ photonic circuits, sensors, electrodes, displays, etc.
 - Mature on-orbit capability to print-on-demand. Parts are printed from computer aided design (CAD) models which can be pre-loaded or uploaded from Earth
- Previously Ames demonstrated printed devices include: strain gauge, chemsensor, pH sensor, biosensor

Printable Spacecraft
Flexible Electronic Platforms for NASA Missions

Kendra Short, Principal Investigator, JPL

Motivation

- Printed Electronics uses soluble functional inks and thin, flexible substrates to fabricate electronic circuit elements (capacitors, TFTs) and functional devices (solar cells, sensors, batteries).
- A Printable Spacecraft is one in which all the functional subsystems are printed and integrated onto a single thin substrate.
- The advantages of the technology comes from the low cost additive manufacturing approach, and the unique form factor: conformal platform, low mass, low volume, low recurring cost, short cycle time, potential for in-space manufacturing.

Task Description

- The NIAC Phase 2: "Printable Spacecraft" – completed in FY14, final report in review.
- Examined the use of printed electronics in NASA engineering, science and human exploration applications
- Developed a reference mission and point design for an multi-functional integrated science sensor "spacecraft".
- Evaluate programmatic benefits for cost, mass and risk.
- Addressed critical technical challenges by developing a bench-top prototype of the integrated sensor spacecraft and performing space environment compatibility testing on material and device coupons.

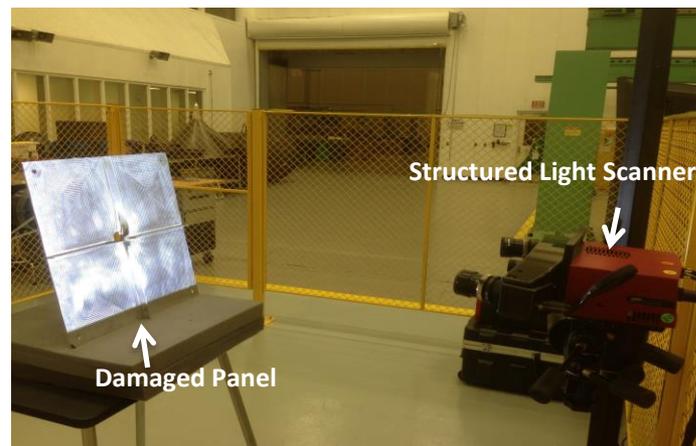
Bench-Top Prototype: An innovative spacecraft sensor platform for conducting in-situ science or distributed engineering measurements

System Functionality	Components										
<ul style="list-style-type: none"> • Multiplexing two independent sensors measurements • ADC and data storage • Wireless communication 	<table border="1"> <thead> <tr> <th>Printed</th> <th>Discrete</th> </tr> </thead> <tbody> <tr> <td>• Thermistor & Photoresistor</td> <td>Processor, ADC, RF chip</td> </tr> <tr> <td>• Resistors & Capacitors</td> <td></td> </tr> <tr> <td>• Antenna & TFTs</td> <td></td> </tr> <tr> <td>• All interconnects</td> <td></td> </tr> </tbody> </table>	Printed	Discrete	• Thermistor & Photoresistor	Processor, ADC, RF chip	• Resistors & Capacitors		• Antenna & TFTs		• All interconnects	
Printed	Discrete										
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• Antenna & TFTs											
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<p>Advances in State of the Art</p> <ul style="list-style-type: none"> • Intersystem multi-functional compatibility of various printed devices and micro-electronics • Low Voltage platform and TFTs • Multiplexing continuous data from multiple sensors. • New sensor design. 											

In-space Additive Repair

- JSC/MSFC: working with JSC and MMOD Office to develop and test process for ground-based repair of MMOD simulated damaged panels for future in-space capability.

Close-up of simulated MMOD Damage to External ISS Panel



Scanning the Damaged Panel

Printable Electronics

- ARC/MSFC/JPL: Develop in-space manufacturing capabilities to produce functional electronic and photonic component on demand.

Printed Electronics for In-Space Manufacturing

(a) Jet printing of inkjet printer
 (b) Inkjet printing of inkjet printer
 (c) Inkjet printing of inkjet printer
 (d) Inkjet printing of inkjet printer
 (e) Inkjet printing of inkjet printer

Labels: CNT, cellulose fiber

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Advances in State of the Art

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- Low Voltage platform and TFTs
- Multiplexing continuous data from multiple sensors.
- New sensor design.

Langley Research Center: Electron Beam Freeform Fabrication (EBF³) Portable Systems for In-Space Simulation Experiments

- First successful microgravity demos February 2006
- Microgravity tests support fabrication, assembly and repair of space structures and in-space manufacturing of spare parts
- Smaller build volume (12" x 12" x 12") with finer wire for more precise deposits minimizing or eliminating finish machining
- Two systems designed and integrated in-house to assess different approaches for reducing power, volume and mass without impacting build volume



POC: Karen.M.Taminger@nasa.gov

- KSC POCs: Jack Fox, Rob Mueller
- Destination Systems Additive Manufacturing
 - GCD Project in collaboration with MSFC and US Army Corps of Engineers: Additive Construction with Mobile Emplacement (ACME) - using indigenous materials (regolith) to construct large scale in-situ planetary infrastructure (e.g. Landing Pads, Blast Barriers, Roads, Hangars, Shelters, Habitats, et.c.)
 - Keck Institute for Space Studies: KSC co-led a prestigious workshop titled “Three Dimensional (3D) Additive Construction for Space using In-Situ Resources”, which included a video recorded short course available at <http://kiss.caltech.edu/study/3D/index.html> . A paper and a Wikipedia article are being written and published to define the state of the art of 3D Additive Construction.
 - New digital materials (voxels) with robotic assembly are being investigated.
 - MSFC 3D printed a titanium housing for a robot harmonic drive / motor housing which has been installed in an excavation robot for testing in the planetary regolith testbed.
 - A CIF project was completed in FY15: 3-D Additive Construction Using Basalt Regolith Fines. Feasibility was proven with a bench top ogive cone printed from basalt with a laser heat source. Materials issues were shown to exist due to internal thermal stresses during cooling.
 - Basalt sintering of materials in a kiln is being researched to understand and quantify desired materials properties.
 - Foamed regolith was produced using an auger feed system with super critical CO2 injection. The foamed regolith is 3-10 times stronger than Portland cement concrete in ultimate bending stress. Preliminary attempts at 3D printing using foamed basalt were promising but not completely successful.

Foundational NDE Methodology for Certification of Additive Manufacturing (AM) Parts and Materials

- **Purpose:** Develop certification methodologies designed to ensure the production of safe and reliable AM parts for spaceflight applications. Emphasis will be placed on metals and AM processes used in fabrication of propulsion system components.
- **Justification:** AM is a rapidly emerging technology and there is a recognized lag in AM process and part validation and certification methodologies. NDE has been identified as one key technology to close this gap.
- **Summary:** The OSMA state of the art AM report will be used to define highest priority needs/gaps for NDE of AM parts. Resources will be used to down select and optimize NDE techniques that will then be combined with NDE modeling for a cost-effective methodology for verifying part quality. A workshop will be held mid year to assess progress and further define needs.

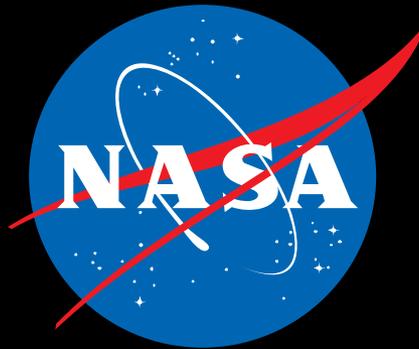
- NASA, including each Mission Directorate, is investing in, experimenting with, and/or utilizing AM across a broad spectrum of applications and projects.
- Centers have created and are continuing to create partnerships with industry, other Government Agencies, other Centers, and Universities.
- In-house additive manufacturing capability enables rapid iteration of the entire design, development and testing process, increasing innovation and reducing risk and cost to projects.
- For deep space exploration, AM offers significant reduction to logistics costs and risk by providing ability to create on demand.
- There are challenges: Overwhelming message from recent JANNAF AM for Propulsion Applications TIM and the American Institute of Engineers Symposium on 3D Printing and Additive Manufacturing for Defense and Government, Additive Manufacturing for Defense and Aerospace, National Space & Missile Materials Workshop on Certification for Additively Manufactured Rocket Engine Components and many other forums is “certification.”
- NASA will continue to work with our partners to address these challenges to advance the state of the art in AM and incorporate these capabilities into an array of applications from aerospace to science missions to deep space exploration.

- In Space Manufacturing: Don't Leave Home (planet) Without It
 - 3D Print ISS Tech Demo has been fully successful as the first step in becoming Earth independent
 - We plan to follow the roadmap, developing new ISS Tech Demos for the Recycler; Printed Electronics; Alternate, Stronger Materials, Metallics, and External (to ISS) Fabrication
- AMD-LPS and LCUSP are effective catalysts for culture change
 - Demonstrated transformative cost and schedule reduction
 - Dramatic reduction in DDT&E cycle time and disruptive change to traditional process
 - Technology testbed to government and industry for future developments
- RS25
 - AM is a key element of Affordability Initiative offering “game changing” capability for cost reduction
 - Baselined components are progressing towards Preliminary Design Review
 - Additional opportunities for AM are continuing to be assessed in trade studies
- Certification approach for AM rocket engine components – another first step
 - Center-level AM requirements draft released for broad review in July 2015
 - Requirements allow innovation while managing risk
- Additive Manufacturing Structural Integrity Initiative (AMSII) will provide the Foundation to address knowledge gaps in certification requirements to better manage AM risk

The “next industrial revolution” is here!

The Future Is Closer Than You Think





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BACK UP

- **NASA Flight Program Motivations in AM**
 - CCP
 - Boeing: no known AM parts planned (currently)
 - SpaceX: numerous parts, AM certification critical path (2017)
 - Superdraco, lox valve body, etc. (next slide)
 - Orion
 - Numerous AM candidate parts under active consideration
 - Passive vent, Aero Blade Seals, RCS components
 - SLS
 - Considerable investment considered for RS-25E
 - Considerable cost savings needed for single-use SSME
 - Candidate AM parts at all levels of complexity and criticality
 - SLS is the primary sponsor of most AM certification efforts
- **NASA AM hardware expected to lead the aerospace industry for implementation of fracture critical flight parts.**

- **Tailoring and Part Classification provide flexibility within the requirements**
 - **Tailoring**
 - Document targets succinct, high-level requirement statements
 - Considerable commentary on intent
 - Allows for user tailoring to intent
 - **Classification**
 - All AM parts are placed into a simple risk-based classification system to help customize requirements according to risk
 - Three decision levels
 - Consequence of failure (High/Low) {Catastrophic or not}
 - Structural Margin (High/Low) {strength, HCF, LCF, fracture}
 - AM Risk (High/Low) {build complexity, access, inspectability}
 - Part classification highly informative relative to part risk.

- **Part Development Plans (PDPs) document the implementation and interpretation of the requirements for each AM part**
 - Content varies with part classification
 - Example Content:
 - Part classification and rationale
 - Witness sampling requirements and acceptance criteria
 - First article evaluations and re-sampling periods
 - Build orientation, platform material, and layout
 - Repair allowance, Inspection requirements, critical dimensions

- **Four types of process control are levied**
 - Metallurgical Process
 - Part Process
 - Equipment Process
 - Vendor Process
- **Each process requires qualifications or certifications**

- Metallurgical Process Constituents
 - Feedstock controls
 - Chemistry
 - Powder morphology (PSD, shape, atomization methods)
 - Fusion process controls
 - Machine type
 - Parameters: laser power, speed, layer thickness, hatch width, etc.
 - Chamber atmosphere
 - Thermal processing controls
 - Governs microstructural evolution
 - As-built through recrystallization
 - Final densification
- When finalized and locked as a process, a *Qualified Metallurgical Process* (QMP) is established and referenced for use in part processes

- Part Process governs all operations needed to produce a given part to defined part process
- Largely documented via drawing and PDP
- Includes every step in part production
 - QMP
 - Build layout
 - Witness specimens and testing
 - Powder removal
 - Platform removal
 - Thermal processing
 - Final machining operations
 - Surface improvement
 - Inspections
 - Part acceptance requirements
- Part Process Control is typically documented through a traveller system. Once established, locked, and approved, the sequence is considered a *Qualified Part Process (QPP)*

- Equipment Process
- Like all process-sensitive equipment, all AM-related equipment requires proper calibration and maintenance
- The scope of such equipment calibration and certification remains to be determined
 - Mechanical
 - Electronic
 - Optical
 - Software
- Control of machines is critical
- How to allow for updates to improve machine performance?
 - Not common for any flight process-sensitive system

- Design vendor
 - Provides the part design and associated CAD
 - CAD model file controls
 - CAD model checking
 - STL file generation

- Build Vendor
 - Developing criteria for approved build vendor list
 - Requires S&MA audit and approval
 - Quality systems in place, e.g. AS9100
 - Manages machine quality control program
 - Electronic file control, part interaction (support structures)
 - Feedstock handling, part handling, nonconformance system
 - Management of aerospace flight quality hardware and process
 - User training and skill requirements
 - Safety protocols

- Material properties often confused with certification
 - Certification >> material properties
- Highly “localized user” process requires different thinking
- Shift emphasis away from exhaustive, up-front material allowables intended to account for all process variability
- Move toward ongoing process monitoring with thorough, intelligent witness sampling of each build
- Hybrid of Statistical Process Control and CMH-17 approach for process-sensitive composite material equivalency
- Utilize a QMP to develop a *Process Control Reference Distribution* (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process
- Enforce suite of design values compatible with PCRDs
- Accept parts based on comparison to PCRD, not design values
- PCRDs are continuously updated, design suite must be monitored and determined judiciously early on
- Allows for adoption of new processes without invalidating large allowables investments